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This paper describes a ship steering system that provides a means to accurately steer a ship along a prescribed track such as a rhumb line, for indefinite distances. This is accomplished by applying frequent heading corrections via a track-keeping interface to the ship's autopilot, based on best present ship position data (BPP) and the prescribed track. Best present position is obtained from an integrated navigation positioning system. The navigation positioning system computer provides best present position as frequently as required, by integrating position data from land based Loran stations, satellite based GPS, an inertial navigation system and dead reckon aids. The prescribed track usually specified as a rhumb line equation for survey applications generally may be described by any desired mathematical representation. The best present position and the mathematical representation of the track used to compute the off-track distance of the ship from the track. The off-track distance is used to develop proportional and integral heading corrections, which are applied to the autopilot by way of the track-keeping interface. The paper includes system performance results of in-house simulations and shipboard operation.

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AN INTEGRATED NAVIGATION APPROACH FOR SHIP TRACK CONTROL

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1. ABSTRACT

This paper describes a ship steering system that provides a means to accurately steer a ship along a prescribed track such as a rhumb line, for indefinite distances. This is accomplished by applying frequent heading corrections via a track-keeping interface to the ship's autopilot, based on best present ship position data (BPP) and the prescribed track. Best present position is obtained from an integrated navigation positioning system. The navigation positioning system computer provides best present position as frequently as required, by integrating position data from land based Loran stations, satellite based GPS, an inertial navigation system and dead reckon aids. The prescribed track usually specified as a rhumb line equation for survey applications generally may be described by any desired mathematical representation. The best present position and the mathematical representation of the track are used to compute the off-track distance of the ship from the track. The off-track distance is used to develop proportional and integral heading corrections, which are applied to the autopilot by way of the track-keeping interface. The paper includes system performance results of in-house simulations and shipboard operation.

2. INTRODUCTION

An integrated navigation approach provides high quality ship position information based on the best combination of available navigation data. The position data used in conjunction with the track-keeping algorithm described herein, is sufficient to guide a ship along a prescribed track. Efficient acquisition of bathymetric, gravimetric and magnetic data is accomplished along prescribed rhumb line tracks. The integrated navigation system consists of GPS and Loran-C receivers, an inertial navigator, electromagnetic and doppler speed logs, and a navigation computer to process and combine all of the available navigation data into the Best Present Ship's Position (BPP). The integration of the inertial navigator and dead reckon aids with GPS and Loran data, allows filtering of any high frequency noise errors of the GPS and Loran data.

Prior to the development of the approach described herein, course corrections for cross track drift were obtained by monitoring a track plot and calling corrections up to the helmsman who set the change into the autopilot. The automated approach to ship's track control, uses the high quality BPP to determine virtually instantaneous cross track errors to drive a proportional plus integral (PI) controller in the navigation computer to derive heading corrections which are applied to the autopilot to maintain the ship on track.

3. TRACK GUIDANCE CRITERIA

A track specification defined as a point on the track and the angle of the track with respect to north (desired ground track) are entered into the navigation computer for application to the track control algorithm. The ship is initially manually steered toward the desired starting position of the track to be surveyed. When within 0.1 nautical miles of the track, the desired ground track (DGT) is set into the autopilot and the automatic track mode is activated. The automatic track-keeping system provides the necessary corrections to steer the ship onto the desired track and keep it on track. Environmental disturbances, such as wind, waves, and ocean currents, that tend to drive the ship off track are compensated for by the automatic track-keeping system and restore the ship to the desired track. The open switch position shown in the functional block diagram of Figure 1 indicates the ship steering control loop prior to the start of the survey line (open loop operation). When the ship reaches the startup tolerance of the track, automatic track control is activated by closing the switch, which adds the track-keeping control law to the steering control mechanization (closed loop operation).

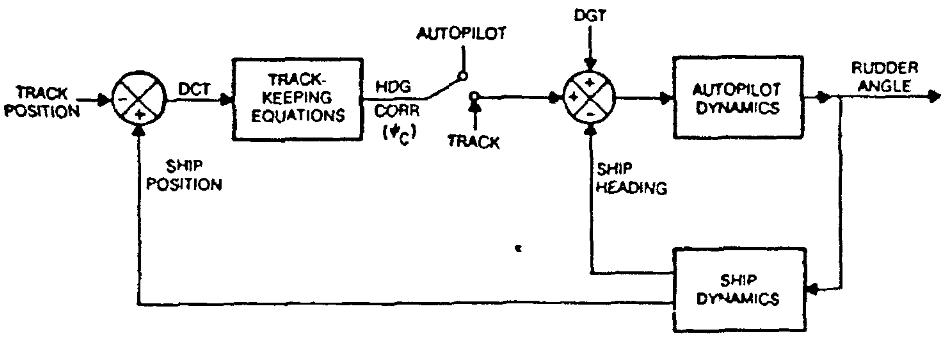
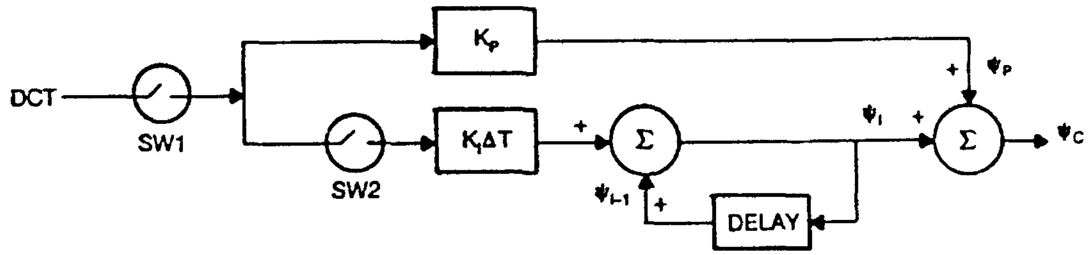


Figure 1. Track-keeping System Functional Block Diagram

4. TRACK CONTROL ALGORITHM DESCRIPTION

The track-keeping algorithm shown in Figure 2 adds proportional and integral heading compensation (PI control) to the autopilot, as required. Switches 1 and 2 provide a means of indicating the application status of the compensation described herein. Excessive integral compensation accumulation, resulting in undesirable overshoot of the track is prevented by applying only proportional compensation (switch 1 is closed and switch 2 is open) until the ship is within 0.1 nautical miles of the track, at which time integral compensation is added (switch 2 is closed). To further minimize the possibility of overshoot and insure a smooth lock onto the track, no proportional or additional integral compensation is added to the autopilot when the ship to track closing velocity exceeds 0.5 knots (i.e, switch 1 is opened when the component of ships velocity perpendicular to and moving toward the track exceeds 0.5 knots). The closing velocity limit provides an alternate form of differential control.



TRACK-KEEPING EQUATIONS

$$\psi_P = K_P \cdot DCT$$

$$\psi_I = \psi_{I-1} + K_I\Delta T \cdot DCT$$

$$\psi_C = \psi_P + \psi_I$$

TRACK-KEEPING EQUATIONS DEFINITIONS

K_P: PROPORTIONAL GAIN

K_I: INTEGRAL GAIN

ΔT: COMPENSATION APPLICATION TIME INTERVAL

DCT: SHIP DISTANCE ACROSS TRACK

ψ_P: PROPORTIONAL HEADING COMPENSATION

ψ_I: INTEGRAL HEADING COMPENSATION

ψ_{I-1}: PREVIOUS INTEGRAL HEADING COMPENSATION

ψ_C: DGT HEADING COMPENSATION

Figure 2. Track-Keeping Control Law, Flow Diagram

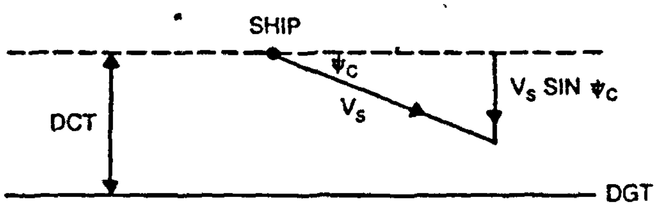
5. ALGORITHM GAIN DETERMINATION

Gain constants Kp and Ki, respectively controlling the proportional and integral compensators, were selected to yield a maximum permissible proportional heading correction of 15 degrees for a ship's off-track distance of 0.1 nautical miles from the track and an integral time (reset rate) Ts, corresponding to a ship's nominal velocity of 15 knots. Using these initial constraints, the gain development in Figure 3 indicates design values of 3 minutes for Ts, and gain values of 150 degrees per nautical mile and 3000 degrees per nautical mile per hour for Kp and Ki, respectively. Using a reduced order model of ship dynamics consisting of yaw and sway, rudder dynamics, and autopilot controller dynamics, application of Liapunov stability analysis techniques verified that the selected design constants yield a stable system. While the system was in fact stable, shipboard testing showed that the steering corrections provided by this controller were too severe for our application, so the Kp and Ki gains were tuned to obtain the desired response.

$$K_P = \frac{\psi_{CMAX}}{DCT_I} = \frac{15^\circ}{0.1\ \text{NM}} = 150^\circ/\text{NM}$$

$$T_S = \frac{DCT_I}{V_S \sin\left(\frac{\psi_{CMAX}}{2}\right)} = \frac{0.1\ \text{NM}}{(15\ \text{KTS}) \sin\left(\frac{15^\circ}{2}\right)} = 3\ \text{MIN}$$

$$K_I = \frac{K_P}{T_S} = \frac{150^\circ/\text{NM}}{3\ \text{MIN}} = \frac{3000^\circ/\cancel{\text{MIN}}\ \text{NH}}{\text{HR}}$$



V_S: NOMINAL SHIP VELOCITY

ψ_C: HEADING COMPENSATION ANGLE

DCT: SHIP DISTANCE CROSS TRACK

Figure 3. Gain Selection Development

6. PERFORMANCE SIMULATION

A ship motion simulation computer program, featuring: linear state space models of the ship's sway, yaw, and roll motions, a non linear surge equation to account for rudder, sway, and coupled yaw/sway drag, and autopilot and steering hydraulics models was employed in the performance simulation. Track-keeping algorithm performance was evaluated through simulations of ship's response to various external factors driving the ship off track. The simulation assumed a ship velocity of 20 knots, a 3 knot ocean current crossing the track at 45 degrees, and a 0.5 nautical mile initial ship offset from the track. The maximum heading correction permitted was 25 degrees for 0.33 nautical mile or greater distance off track, and 15 degrees otherwise. The maximum incremental heading correction permitted was initially 2 degrees. Further testing subsequently resulted in 0.5 degrees being chosen as the incremental heading correction limit. Integral compensation updates were only introduced when the ship's distance cross track was 0.1 nautical mile or less.

The autopilot heading correction, ship's distance cross track and PI control law graphs, provided in Figures 4, 5, and 6, respectively, were generated from the simulation. The negative and positive constant slope portions of Figure 4, reflect time frames in which the theoretical PI control law correction exceeded the maximum 2 degree per increment applied correction limitation. In Figure 4, the size of an increment is indicated by the vertical distance between successive plot symbols. The left and right flat portions of the graph, respectively, indicate a 25 degree maximum heading correction for ship's off track distance of 0.33 nautical miles or more, and a 15 degree maximum heading correction otherwise. Finally, the curved portion of Figure 4 indicates those times where less than maximum allowable incremental heading corrections were required.

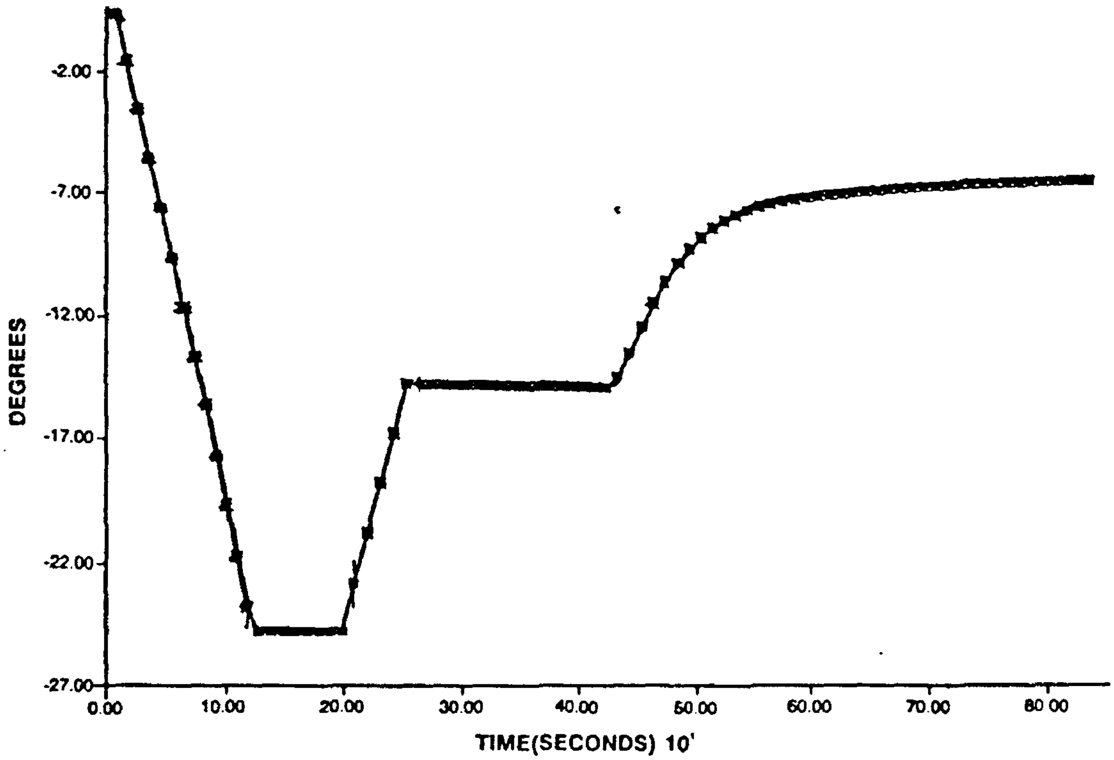


Figure 4. Autopilot Heading Correction Commands

Figure 5 reflects the ship's off-track distance in response to the combination of: the applied heading corrections indicated in Figure 4, the ocean current environment, the ship's initial offset from the track, and the ship's velocity. Due to the 2 degree per increment heading correction application limit, the effect of the ocean current causes the ship to initially move further away from the track, as indicated at the start of the run. As the heading correction application increased to the 25 degree limit permitted for offsets of 0.33 nautical miles or more, the off-track distance decreases rapidly. When the off-track distance falls below 0.33 nautical miles, the maximum heading correction application is reduced to 15 degrees, resulting in a corresponding decreased rate of ship movement toward the track. Finally, as the off-track distance falls below 0.1 nautical miles, the proportional heading correction gradually diminishes, while the integral compensation commences. Integral compensation builds up to the heading correction value required to compensate for the steady state ocean current at the point of reaching zero off-track distance.

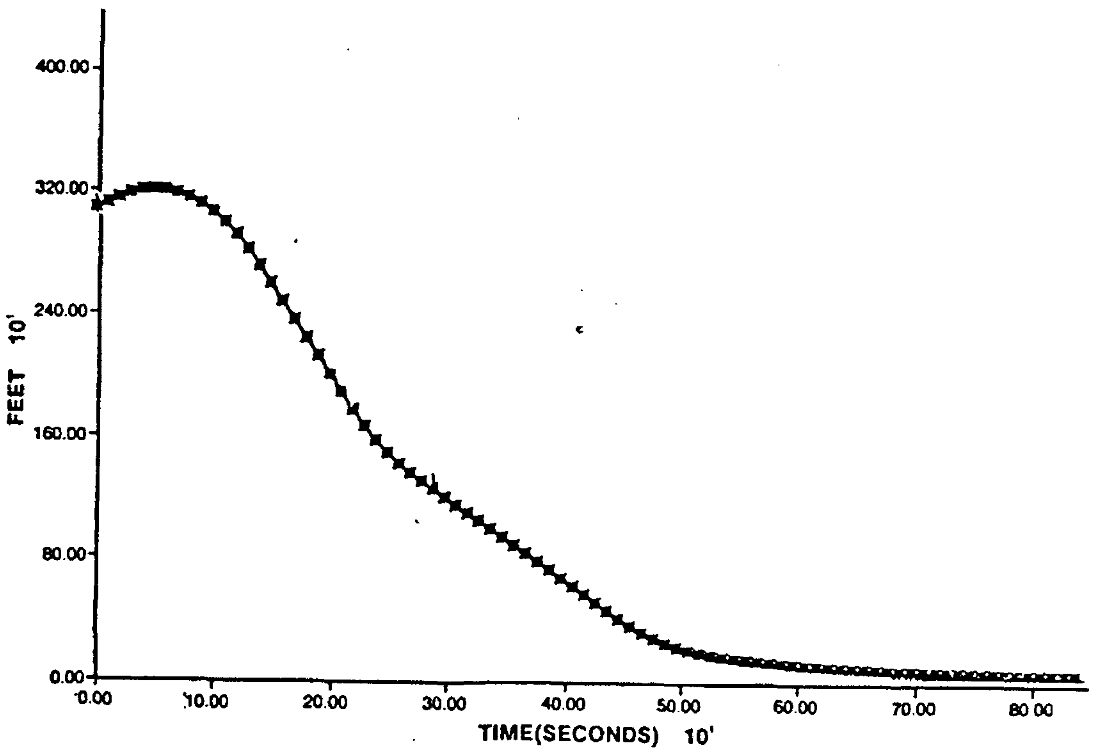


Figure 5. Simulated Ship's Off-Track Distance

Figure 6, demonstrates the proportional and integral corrections generated by the PI control law. The proportional correction graph is identical in shape to the ship's off-track distance graph of Figure 5. In accordance with the correction application criteria, discussed above, the integral compensation graph indicates zero values for ship off-track distances in excess of 0.1 nautical miles, and gradual accumulation to the value required to compensate for the ocean current, in the 0.1 nautical mile off-track distance range.

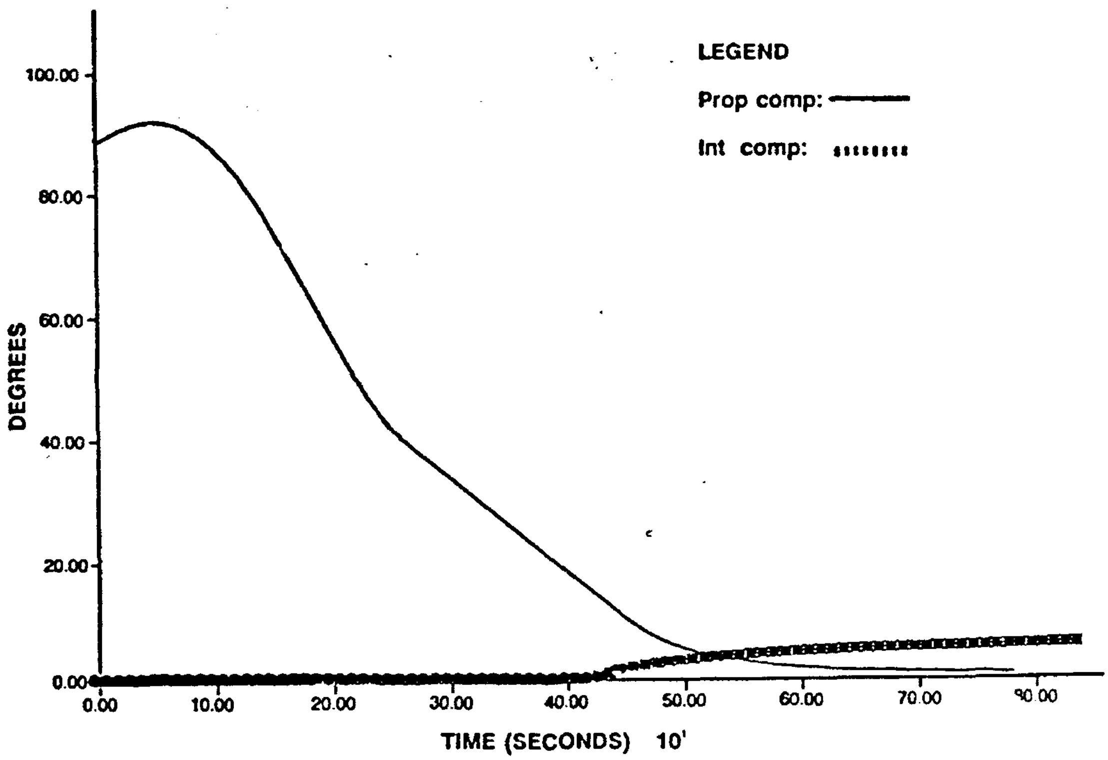


Figure 6. Simulation Computed Proportional and Integral Heading Corrections

7. TRACK-KEEPING IMPLEMENTATION

The automatic track-keeping system was implemented on several survey ships with varying host computers and ship configurations as shown in Figure 7. The PI controller algorithm was hosted in the existing navigation computer and an electrical interface was developed to handle data communications between the navigation computer and the ship's autopilot equipment. The track-keeping interface included digital-to-analog conversion functions and provided options for communications with two different types of host computers, namely, the AN/UYK-20 Navy Standard mini-computer and the HP-1000 E commercial mini-computer. Figures 8 and 9, respectively, show the configuration of the track-keeping interface designed for the two types of host computers. Autopilot configuration modifications entailed incorporation of circuitry to add PI controller derived heading corrections to the selected heading. This permitted the autopilot system to function normally in all other respects so as to seek and lock onto the selected DGT. However, in this case PI controller corrections cause the autopilot system to steer a rhumb line survey track instead of a constant heading.

Finally, sea tests were conducted to fine tune design constants for each ship's implementation. The robustness of the design was evidenced by the fact that successful implementation was achieved with only minimal parameter tuning for ships with widely divergent characteristics.

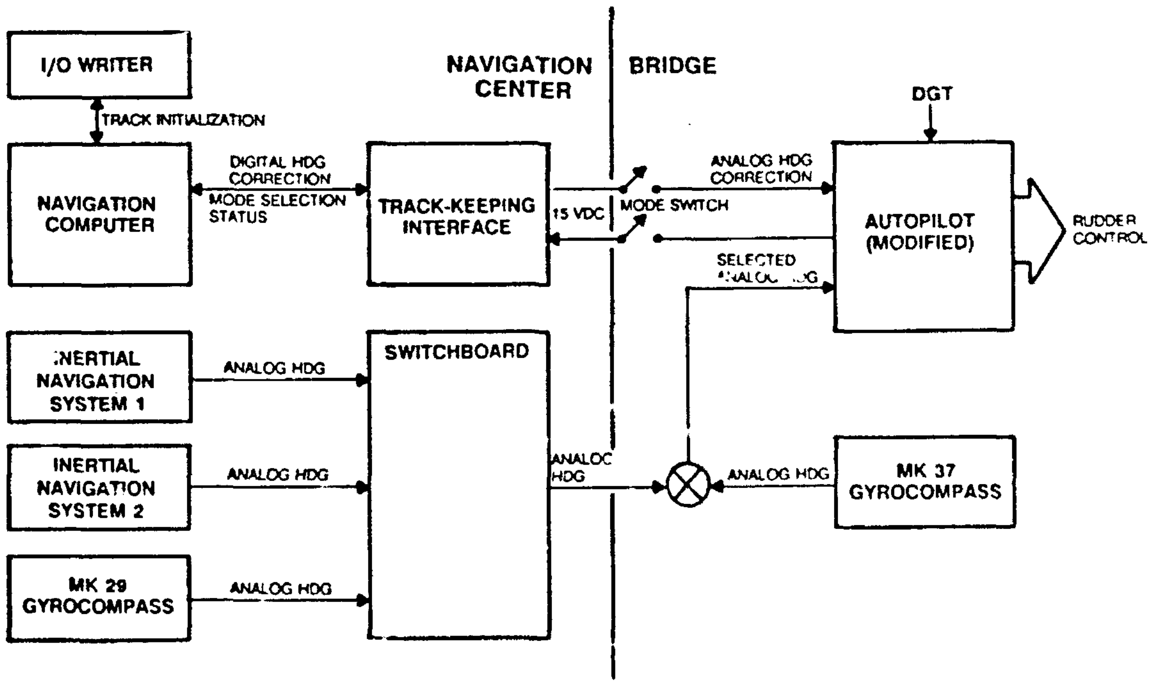


Figure 7. Track-Keeping System Integration

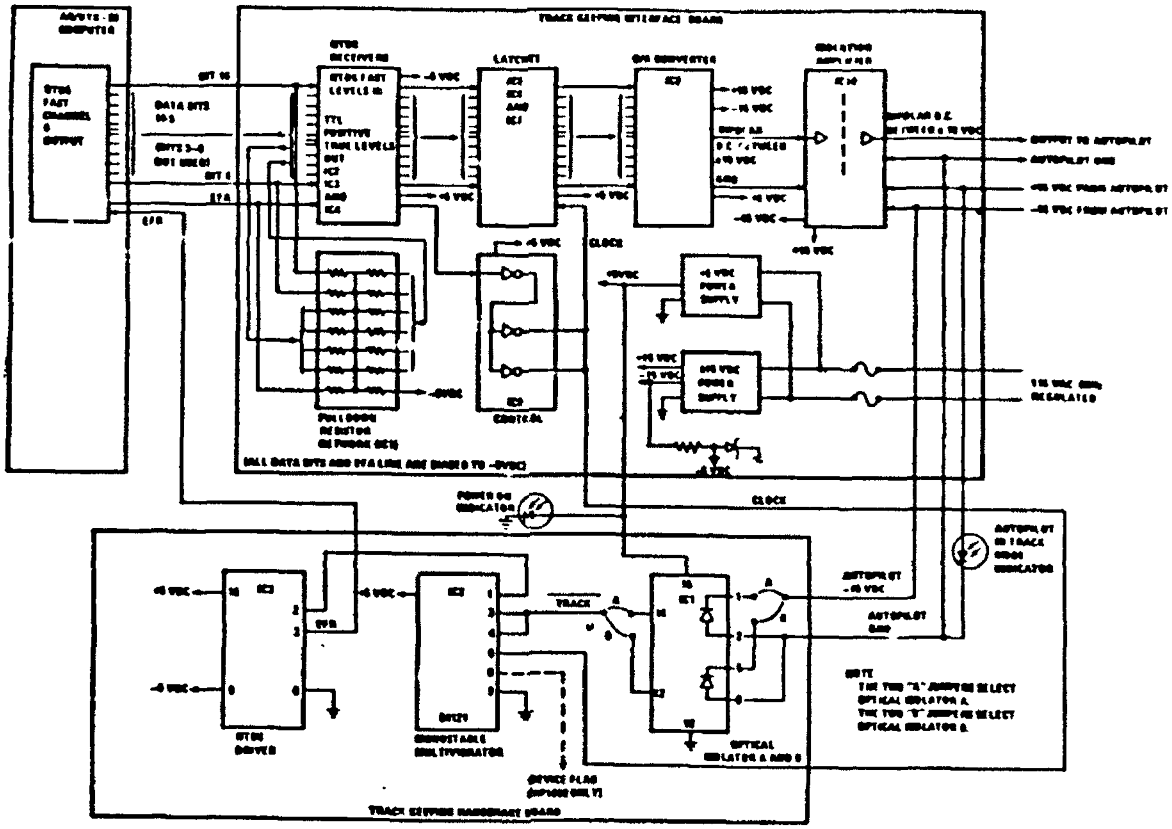


Figure 9. Track-Keeping Interface Block Diagram, AN/UYK-20 Configuration

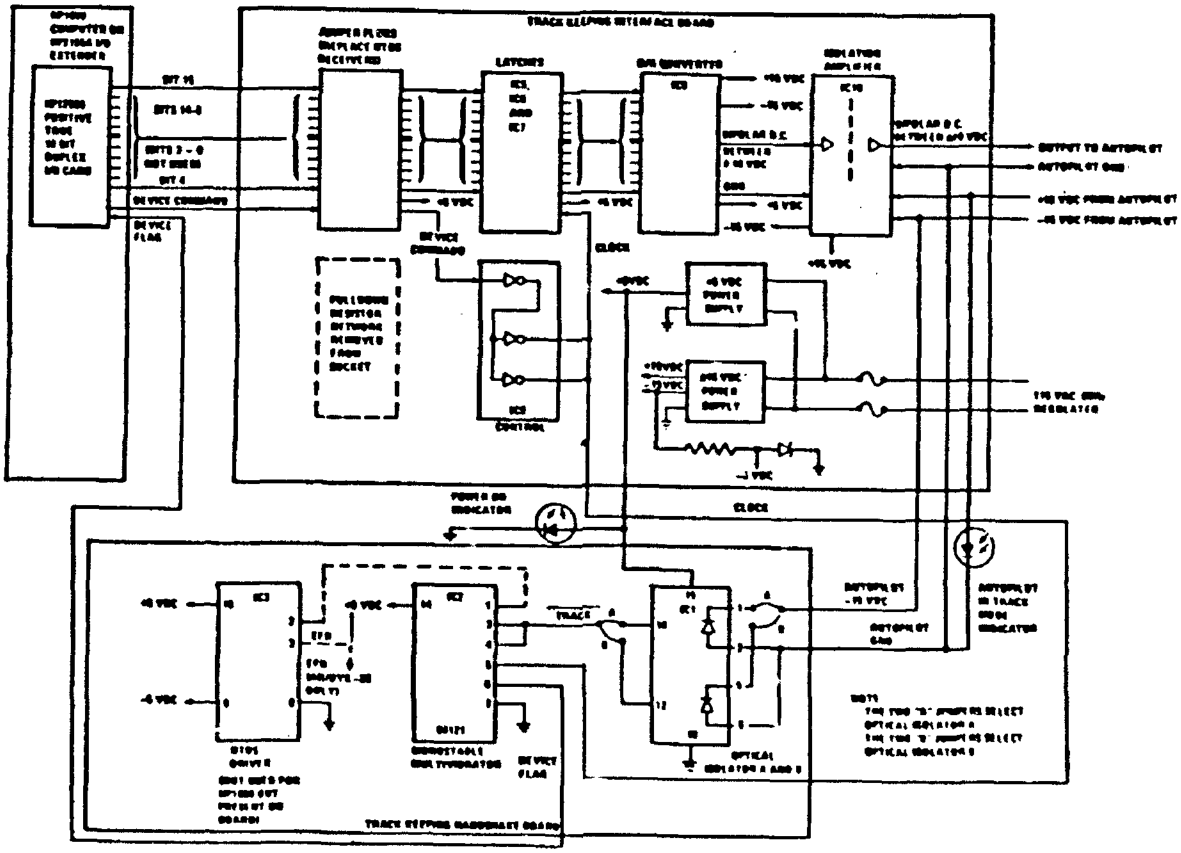


Figure 10. Track-Keeping Interface Block Diagram, HP 1000 Configuration

8. SHIPBOARD PERFORMANCE

The integrated navigation approach to control ship's track was implemented aboard ship and has performed as expected. Especially high quality track control has been consistently achieved with the availability of GPS position. Figure 10 demonstrates two shipboard track repeatability runs obtained in a broad ocean environment. The nearly complete overlap achieved in each case attests to the performance of the integrated navigation approach to control ship's track. Track repeatability to less than 120 feet has typically been achieved.

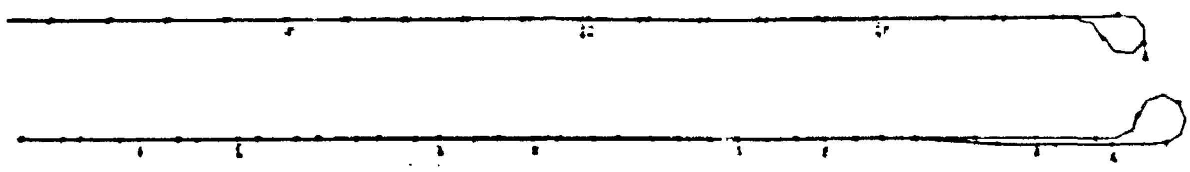


Figure 10. Ship's Track Repeatability Demonstration

9. CONCLUSION

The feasibility of an integrated navigation approach for ship's track control has been successfully demonstrated by simulation and actual shipboard use. The quality of the track-keeping performance is directly tied to the quality of the navigation data available. The integration of GPS and Loran radio navigation data with an inertial navigator and dead reckoning aids provides higher quality data under varying conditions than any single source of navigation data alone, thereby improving the quality of the track-keeping function.

AUTHOR BIOGRAPHIES

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Mr. Leblang received a Bachelors Degree in Electrical Engineering from the City College of New York in 1969 and a Master of Science Degree in Electrical Engineering from New York University in 1973. He was first employed in 1969 by ITT Defense Communications Division in Nutley, New Jersey, where he designed portions of microwave receiving systems. In 1971, he joined Naval Strategic Systems Navigation Facility, Brooklyn, New York, where he was involved in the integration of precise navigation systems for deep ocean survey. This function was transferred to the Naval Air Development Center, Warminster, Pennsylvania in 1973, and was realigned as the Naval Command, Control and Ocean Surveillance Center RDT&E Division Detachment, Warminster in 1992, where Mr. Leblang performs various assignments in the field of navigation system development, integration, analysis and testing.

JULES KRIEGSMAN

Mr. Kriegsman received a Bachelors Degree in Electrical Engineering from the City College of New York in 1959 and a Masters Degree in Electrical Engineering from Polytechnic Institute of Brooklyn in 1970. He is a licensed Professional Engineer. He started working in the field of navigation in 1959 at the Bendix Corporation in Teterboro, New Jersey, where over the next seven years he developed stability requirements for the gyro stabilized platform for the Pershing missile. He then worked one year at the EDO Corporation located in College Point, New York, where he designed stabilized networks for minesweeping sensors. Since 1968 Mr. Kriegsman has been employed with the Department of the Navy, first at the Naval Strategic Systems Navigation Facility at the Brooklyn Navy Yard, and then at the Naval Air Development Center in Warminster, Pennsylvania as the result of a base transfer in 1973. The navigation function of the Naval Air Development Center was realigned as the Naval Command, Control and Ocean Surveillance Center RDT&E Division Detachment, Warminster in 1992. Mr. Kriegsman performs various assignments in the field of navigation system analysis and design.